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Jiang et al.

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(54) **NANOSTRUCTURED COATED SUBSTRATES FOR USE IN CUTTING TOOL APPLICATIONS**

28/044 (2013.01); *B23B 2224/04* (2013.01);
B23B 2224/36 (2013.01); *B23B 2228/04*
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(71) Applicant: **P&S Global Holdings LLC**, Houston, TX (US)

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CPC . *C23C 16/34*; *C23C 16/36*; *Y10T 428/24355*;
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See application file for complete search history.

(72) Inventors: **Wenping Jiang**, Fayetteville, AR (US);
Mike Kimmel, Rogers, AR (US); **Ajay P. Malshe**, Springdale, AR (US)

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(73) Assignee: **P&S GLOBAL HOLDINGS LLC**, Houston, TX (US)

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 31 days.

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Primary Examiner — Laura A Auer
(74) *Attorney, Agent, or Firm* — Robert Devin Ricci;
Richard Lee Vail; Kean Miller, LLP

(65) **Prior Publication Data**

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(57) **ABSTRACT**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/450,787, filed on Apr. 19, 2012, now abandoned.
(Continued)

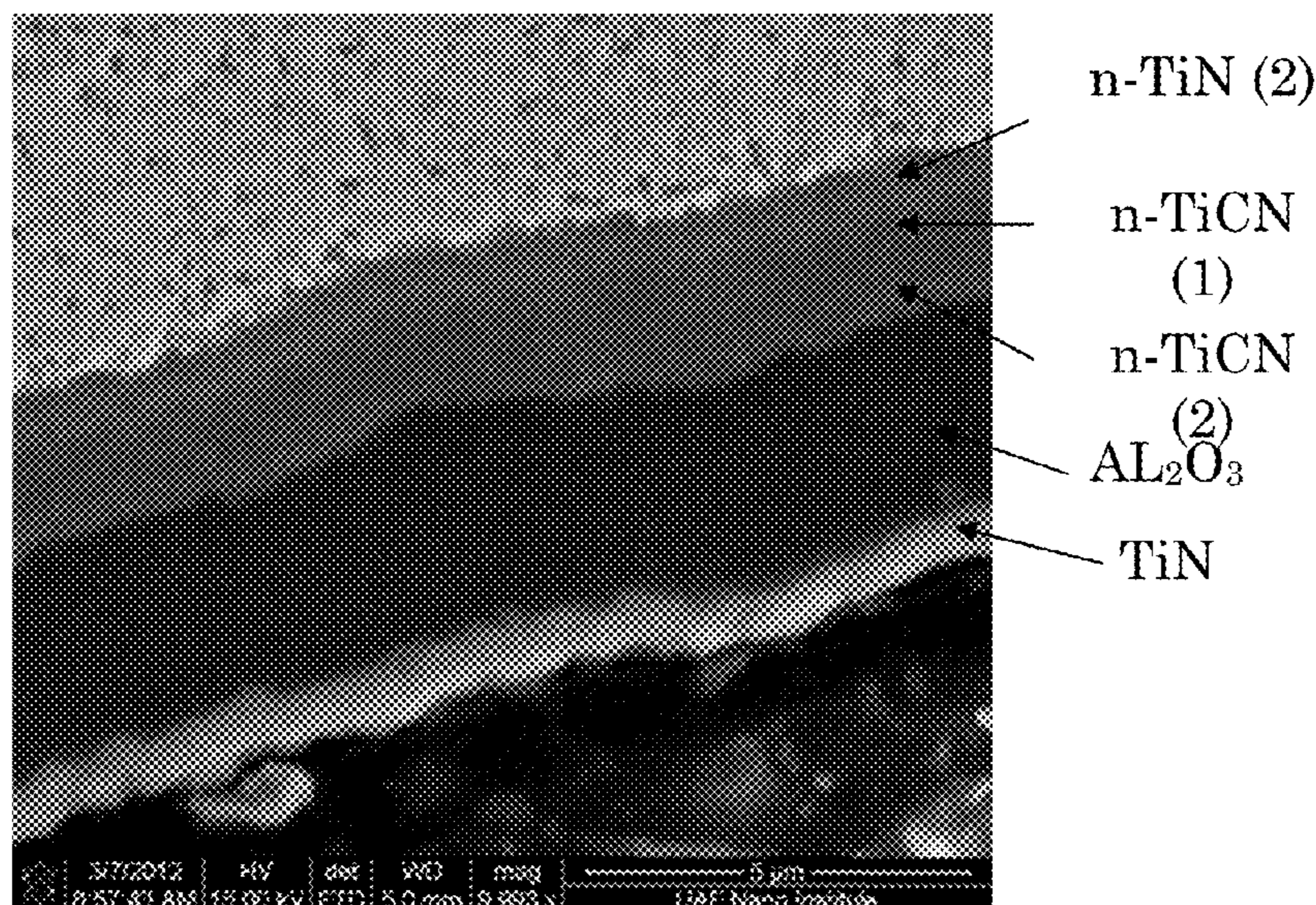
A coating for carbide substrates employs a nanostructured coating in conjunction with a non-nanostructured coating. The nanostructured coating is produced by the addition of a refining agent flow, particular hydrogen chloride gas, during deposition, and may be produced as multiple individual nanostructured layers varying functional materials in a series. The combination of a nanostructured coating and non-nanostructured coating is believed to produce a cutting tool insert that exhibits longer life. Pre-treating the substrate with a mixture of compressed air and abrasive medium prior to coating the substrate and post-treating the coated substrate with a mixture of water and abrasive medium after the coating process is believed to further enhance the wear resistance and usage life of the cutting tool.

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C23C 16/02 (2006.01)

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(2013.01); *C23C 16/34* (2013.01); *C23C 16/36*
(2013.01); *C23C 28/00* (2013.01); *C23C*

10 Claims, 4 Drawing Sheets



Related U.S. Application Data

(60) Provisional application No. 61/601,081, filed on Feb. 21, 2012, provisional application No. 62/300,634, filed on Feb. 26, 2016.

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C23C 16/36 (2006.01)
C23C 28/00 (2006.01)
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B82Y 40/00 (2011.01)

(52) **U.S. Cl.**

CPC *B23B 2228/105* (2013.01); *B82Y 30/00* (2013.01); *B82Y 40/00* (2013.01); *Y10T 428/24355* (2015.01); *Y10T 428/265* (2015.01)

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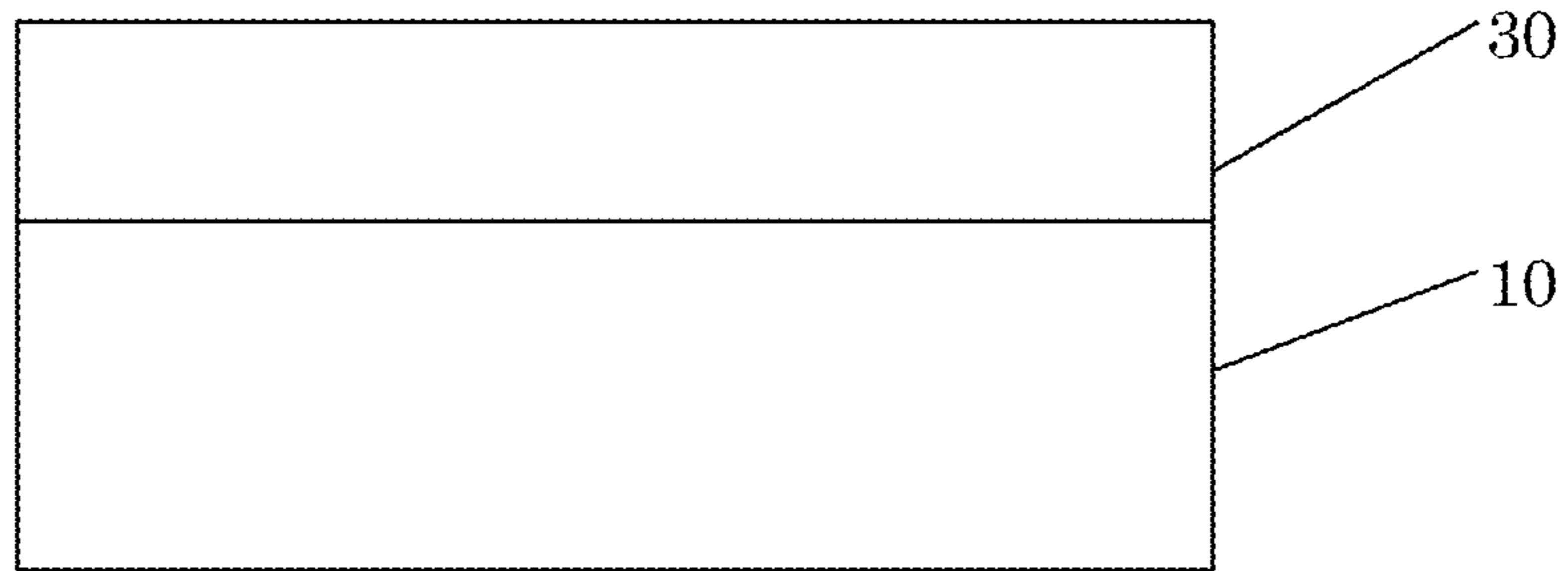


FIG. 1

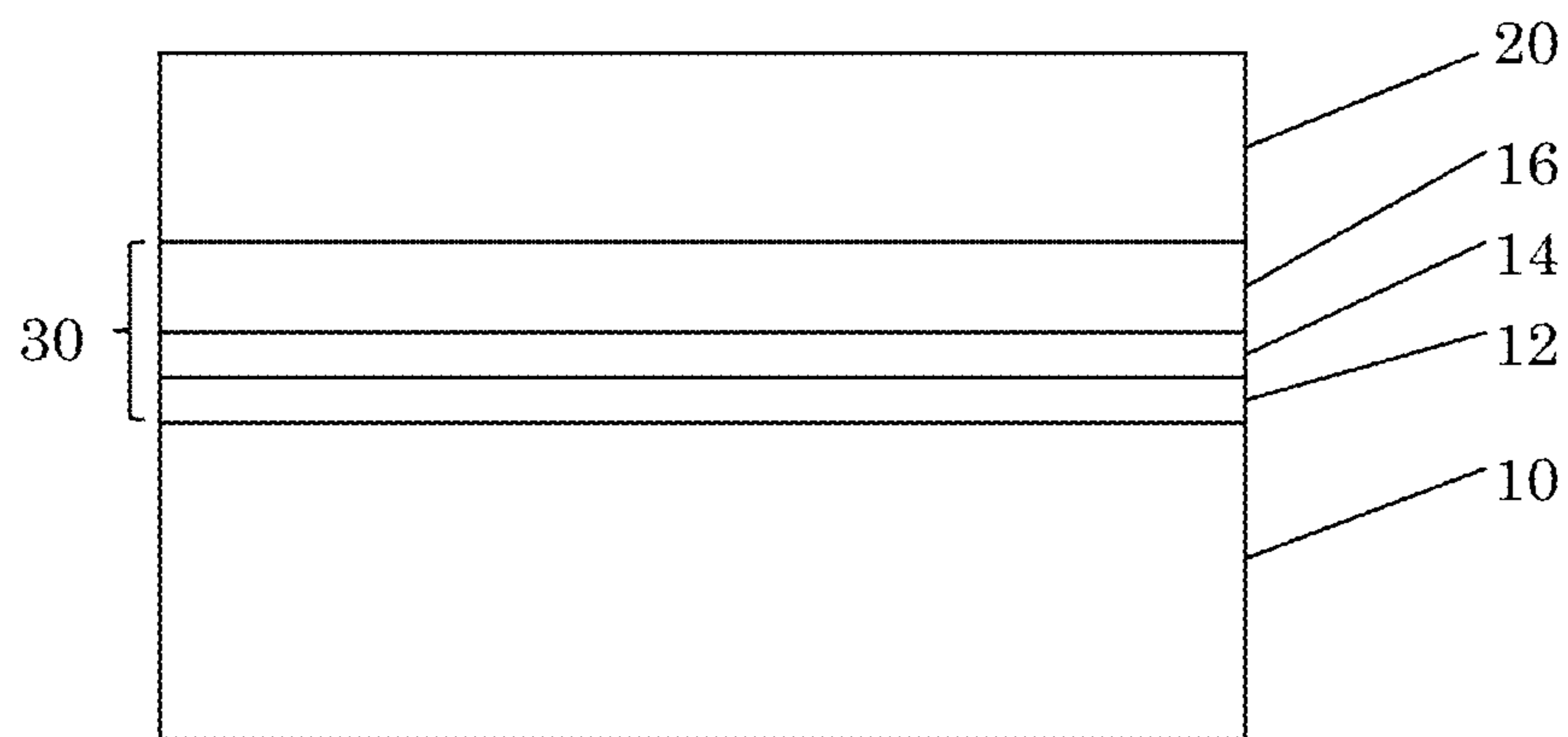


FIG. 2

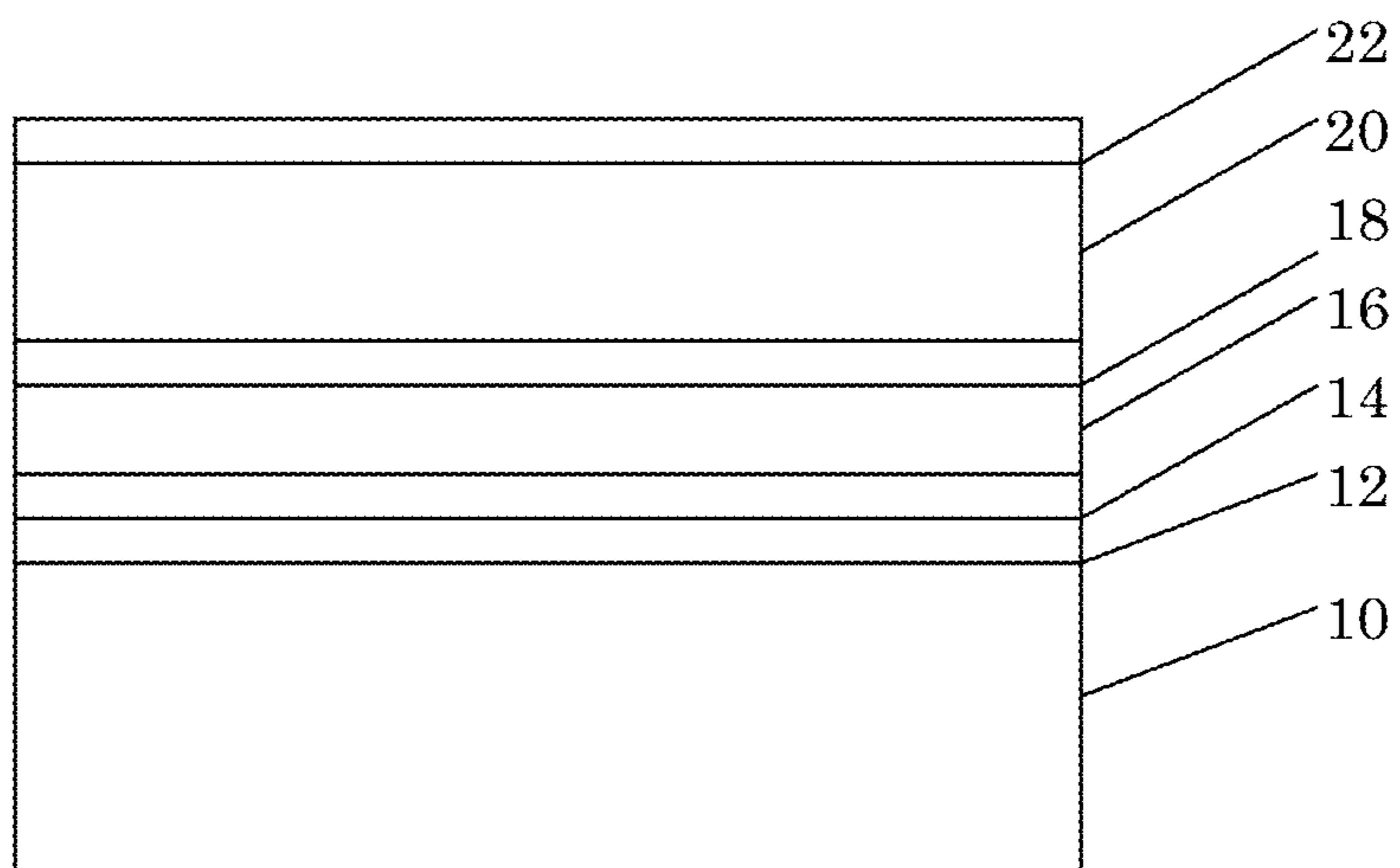


FIG. 3

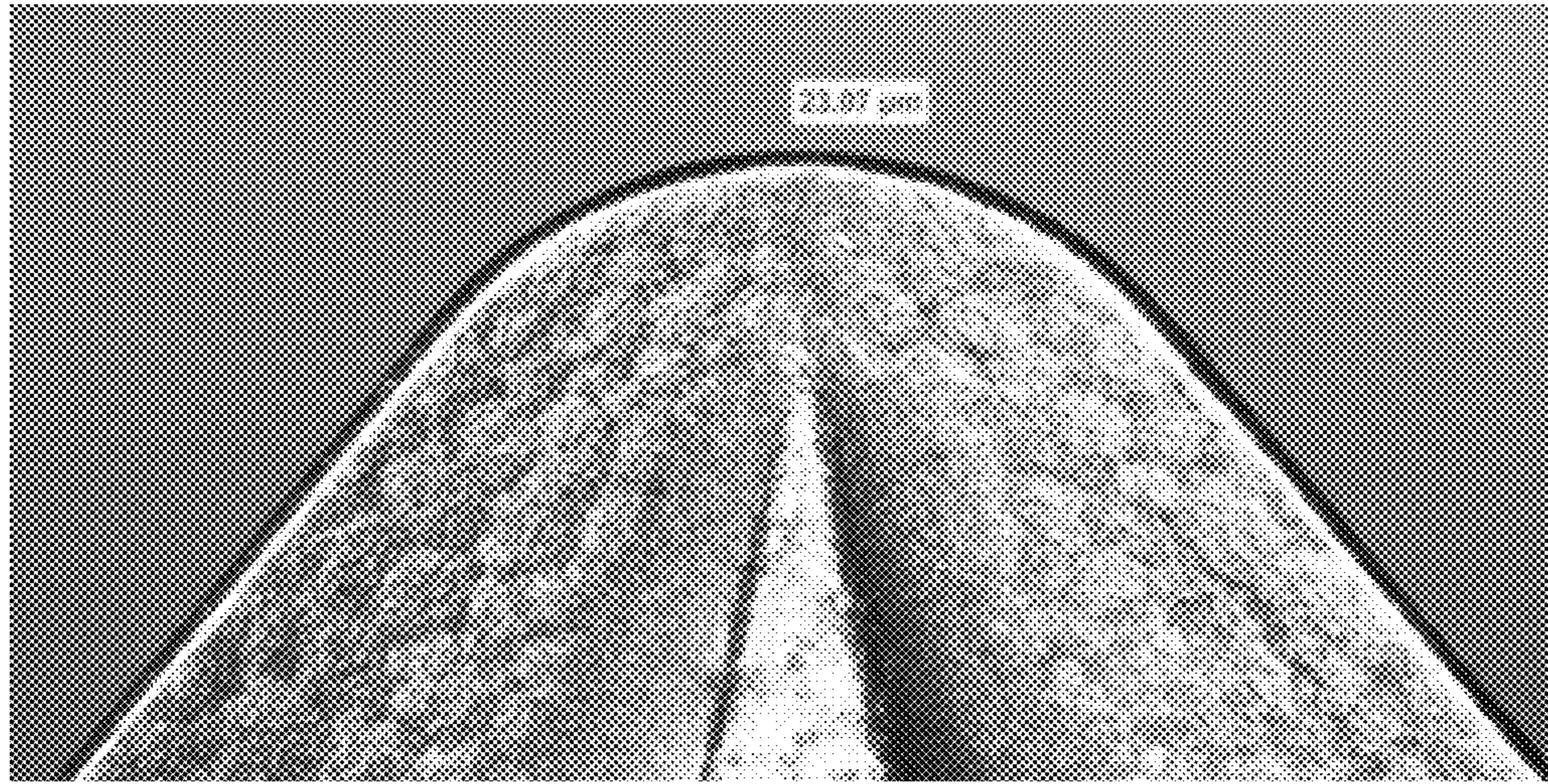


FIG. 4

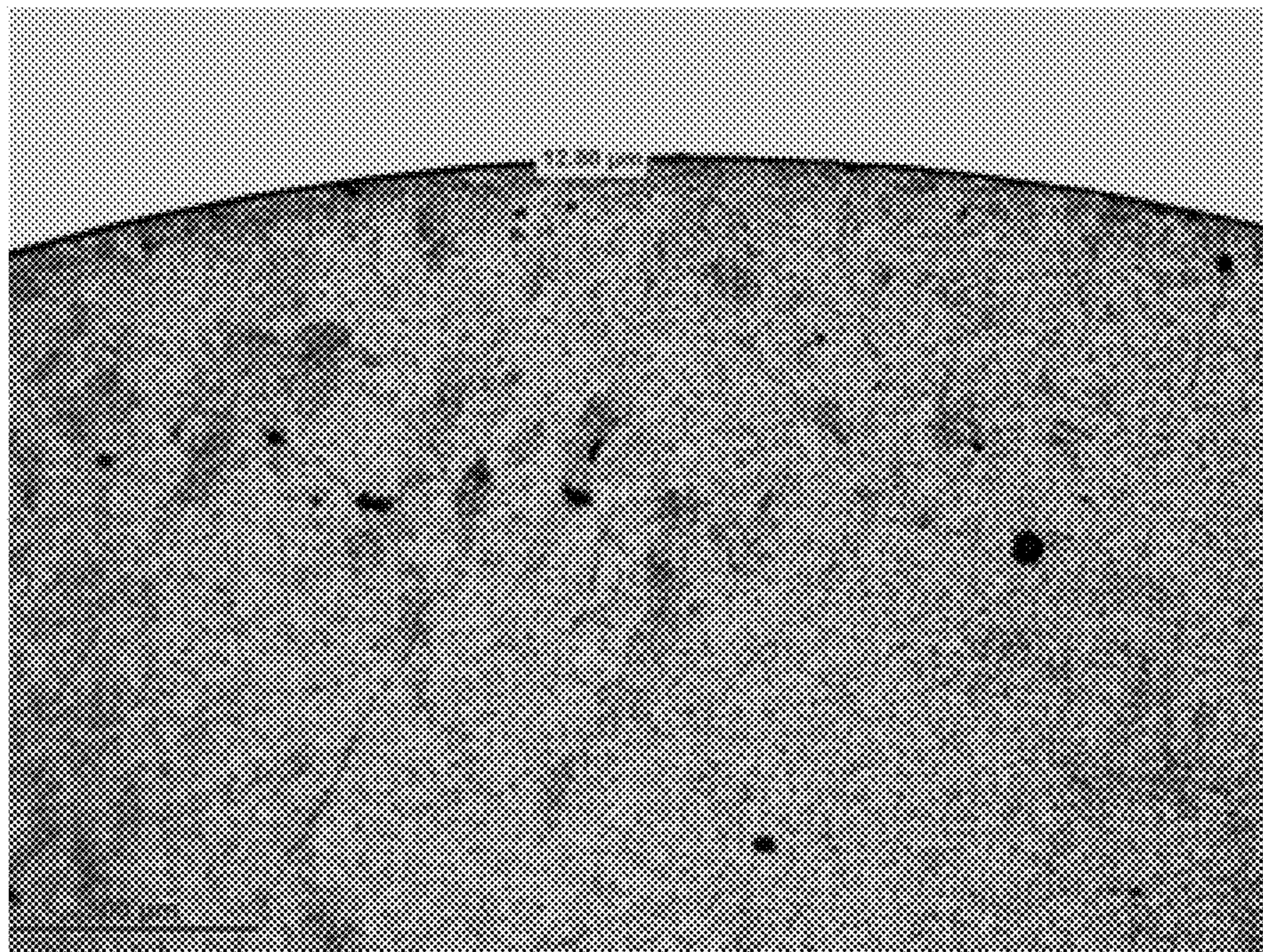


FIG. 5

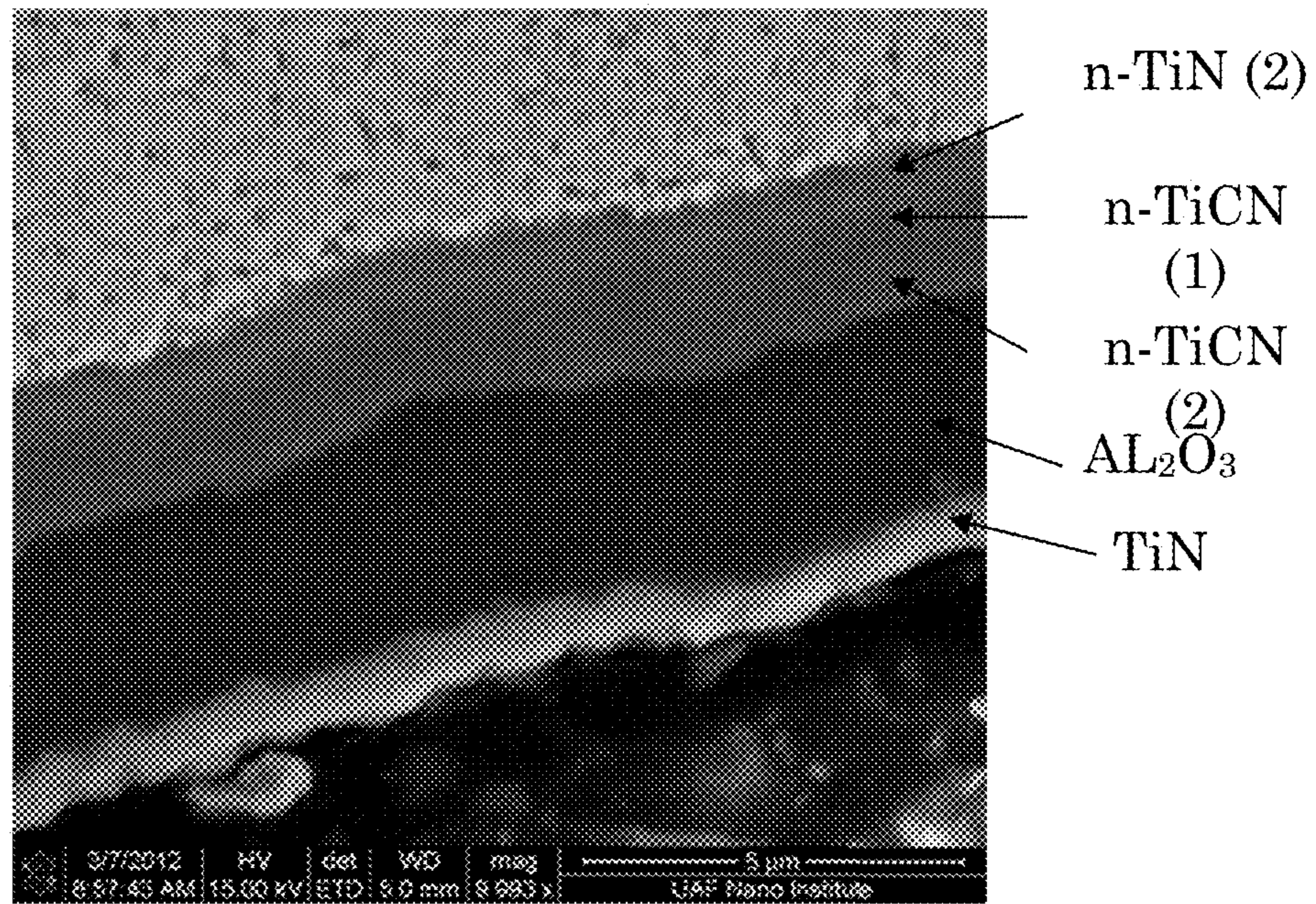


FIG. 6

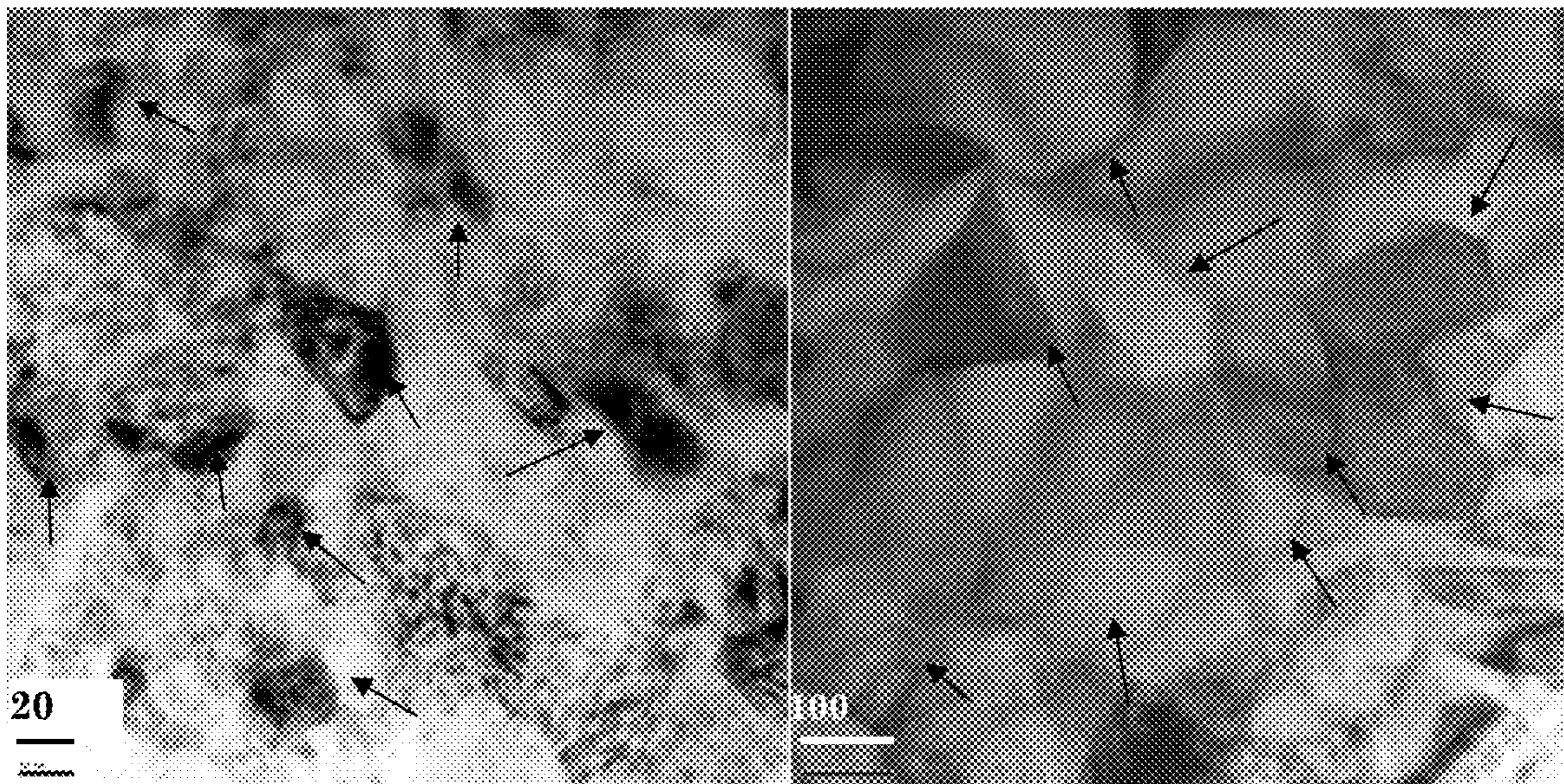


FIG. 7A

FIG. 7B

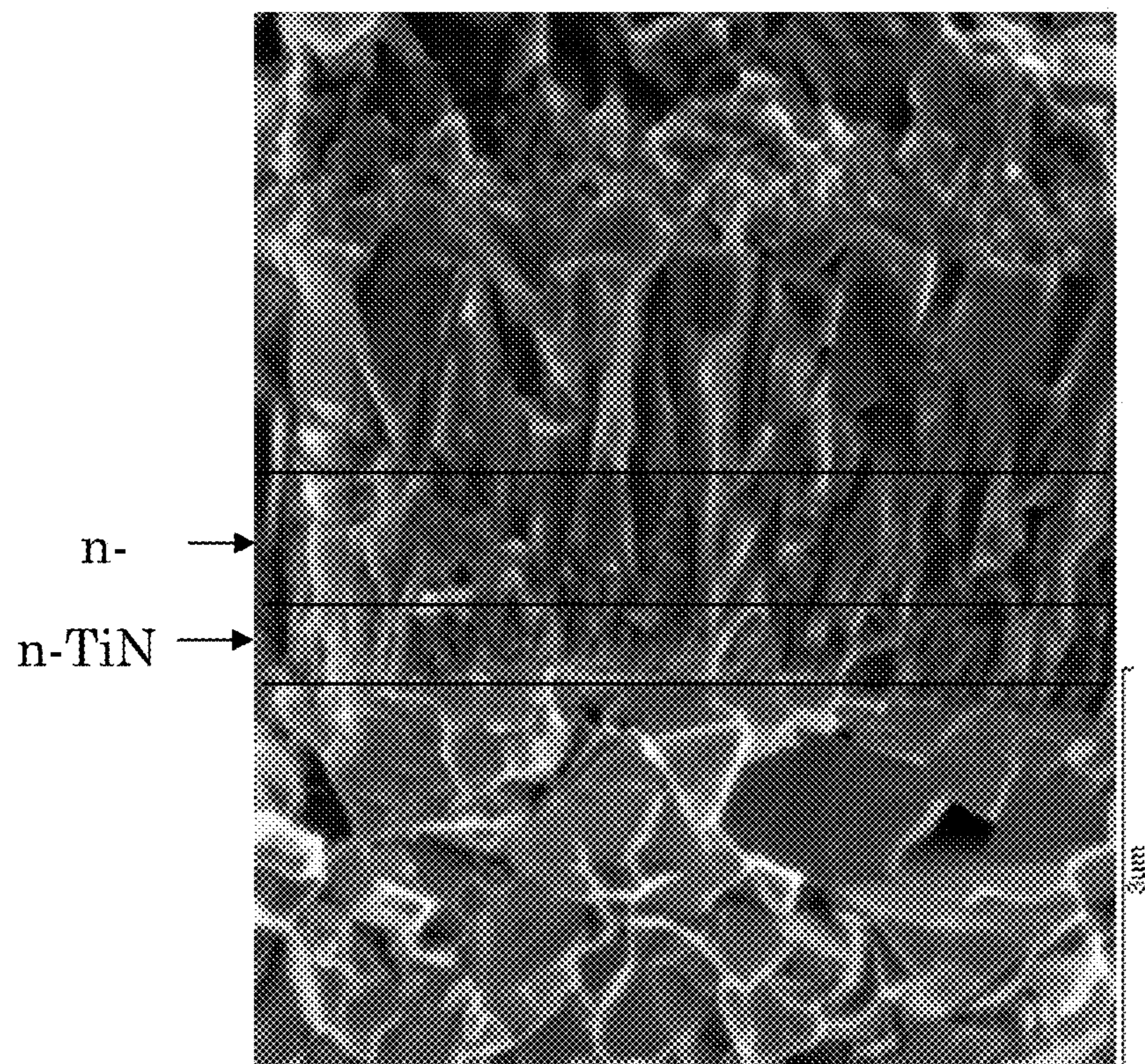


FIG. 8

**NANOSTRUCTURED COATED SUBSTRATES
FOR USE IN CUTTING TOOL
APPLICATIONS**

CROSS-REFERENCE TO RELATED
APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 13/450,787, filed on Apr. 19, 2012, and entitled "Nanostructured Multi-Layer Coating", which claims priority from U.S. provisional patent application No. 61/601,081, filed Feb. 21, 2012, and entitled "Nanostructured Multi-Layer Coating on Carbides." This application also claims priority from U.S. provisional patent application 62/300,634, filed Feb. 26, 2016, and entitled "Coated Carbide Cutting Tools." Such applications are incorporated by reference in their entireties.

STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH OR DEVELOPMENT

Not applicable.

BACKGROUND OF THE INVENTION

Coatings are effective for improving the performance of various materials, such as for achieving better wear resistance and corrosion resistance. Common applications where a coating is applied to a substrate to improve wear resistance of the substrate material include cutting tool inserts for the cutting of hard materials, such as hardened steel with interruptions, and the machining of heat-resistant alloys. Common substrate materials for cutting tools may include, for example, hard metals of different particle sizes with a varied percentage of cobalt or nickel as a binder material. Wear on the coatings of cutting tool inserts is a well-recognized problem, particularly in connection with certain difficult cutting applications.

One such application is the cutting of hard metals with severe interruptions. Coatings applied to carbide substrates produced using chemical vapor deposition (CVD) processes, a common technique, may be chipped off, resulting in premature failure of the cutting tool insert, or exhibit excessive flank wear, again leading to poor performance for the cutting tool insert. Multiple-layer coatings have been developed for cutting tool inserts as attempts to solve this problem. Nevertheless, improved performance is still desired in order to increase the wear life of cutting tool inserts, particular those used with particularly difficult applications, such as the cutting of hardened steel with interruptions.

Another application that presents significant challenges is the machining of heat-resistant alloys. Such applications impose challenges including excessive heat generation at the tool-workpiece interface, workpiece hardening, and expedited tool wear including notch wear. Because of these challenges, machining of heat resistant alloys has generally been limited to relatively low material removal rate (i.e. low surface speed and feed rate). Advances including tool material formulation development, chip breaker design, edge honing, and coating formulation have been made to address these challenges, but problems still remain.

Standard C2 (i.e., soft) carbide grade materials with up sharp edge (i.e., no edge preparation after grinding) in uncoated form have been used for machining heat-resistant alloys. The inventor hereof has recognized that to meet the challenges associated with machining of heat-resistant alloys, an outer adherent coating layer on carbides with

submicron and micron sized tungsten carbide (WC) grains, coupled with 5.0-12% cobalt (Co) binder, is necessary, as this combination can provide thermal management for reducing thermal deformation and degradation. The combination can also provide balanced hardness and toughness and resistance to notch wear. In terms of edge preparation, up sharp edge on many carbide tools provides the needed edge for shearing the materials, and thus reduces the heat generation at the tool-workpiece interface due to relatively low pressure at the interface. Up sharp edge also helps to defer the initiation of notch formation on the leading side of the cutting edges. However, the up sharp edge tends to chip or break due to unstable machining settings, including machine setup rigidity, interruptions, or out-of-roundness on workpieces. The chipped edge, in turn, increases cutting forces and therefore increases heat. This causes further degradation of workpiece surface finishes.

One option for ceramic materials, polycrystalline boron nitride-based cutting tools, and some carbide inserts, is the application of a T-land or K-land on the cutting edge to prevent edges from microchipping. The cutting edge is thus ground to a relatively flat surface from its original curved point that would result from a radius hone. While this provides the necessary edge protection, it typically results in significant heat generation, which further degrades workpiece surface finishes. Thus, a proper edge hone that can protect the cutting edge from chipping, while providing the needed sharpness for shearing the workpiece materials, is critical for machining heat resistant materials. Furthermore, adherent coatings on cutting tool materials have substantially increased the productivity of machining. Coated tools typically run at a much higher surface speed and feed rate than their counterpart uncoated tools. Due to high heat generation involved in heat-resistant alloy machining, proper coating chemistry, coating thickness, and structure is critical.

Both of these applications provide examples of scenarios for which an improved application of substrate coating is needed to improve the functional characteristics and performance capabilities of cutting tool inserts. A properly coated substrate according to the present invention is shown to improve performance by decreasing wear and tear and increasing the performance life of the tool.

BRIEF SUMMARY OF THE INVENTION

The present invention is directed to a nanostructured adherent coating on a substrate for enhancing the wear resistance performance of the substrate. The nanostructured coating may be a single nanostructured layer of functional particles or may be a nano-structured layer comprising multiple sub-layers each comprising functional particles. In one alternative embodiment, the coated substrate may comprise a non-structured layer in conjunction with the nano-structured layer and in other alternative embodiments the coated substrate may comprise optional additional layers. Further, pre-treatment of the substrate prior to the coating and post-treatment of the substrate after coating may be implemented to further enhance the wear resistance performance of the coated substrate. A coating according to the present invention shows improved hardness and toughness, which reduces edge chip-off and flank wear, particularly in difficult applications such as machining hardened steel with interruptions or machining of heat-resistant alloys. The surface processing and treatment allows manipulation of stress and related properties, which in turn further extends the performance of the substrate in various applications.

In a first aspect, the invention is directed to a cutting tool insert, comprising a substrate with a nanostructured coating deposited over the substrate. The nanostructured coating layer may be configured as a single layer comprising a number of functional particles (for example, FIG. 1) or as a series of sub-layers each comprising a number of functional particles (for example, FIG. 2). In the preferred embodiment, a non-nanostructured coating is deposited over the nanostructured coating to create a nanostructured-to-non-nanostructured interface. Preferably the non-nanostructured coating at least comprises a non-nanostructured layer of aluminum oxide (as shown in FIG. 2), which is believed to act as a thermal barrier. In alternative embodiments, as shown in FIG. 3, additional optional layers may be further deposited over the substrate. These additional optional layers may include, for example, additional non-nanostructured coating layers and a capping layer, or other optional layers. In yet another embodiment, the substrate may be pre-treated prior to coating the substrate coated with the coating layer(s) and post-treated after the coating process to further enhance the wear resistant capabilities of the cutting tool insert.

In a second aspect, the invention is directed to a method for producing a coated substrate in a reactor, surprisingly using high-temperature chemical vapor deposition (CVD) techniques rather than traditional low-temperature physical vapor deposition (PVD) techniques. In one embodiment, in which the nanostructured coating is a single layer comprising a number of particles, the coating method comprises the step of depositing a plurality of particles on the substrate in a layer in conjunction with the release of a refining agent flow to produce a nanostructured layer. Alternatively, for an embodiment in which the nanostructured coating layer comprises multiple sub-layers, the method may comprise the steps of depositing a first material on the substrate in a layer in conjunction with the release of a refining agent flow to produce a first nanostructured layer, depositing a second material on the substrate in a layer in conjunction with the release of a refining agent flow to produce a second nanostructured layer, and repeating for more additional nanostructured layers if desired. In the preferred embodiment, the method further comprises depositing an additional material on the substrate to produce a non-nanostructured layer over the substrate. This layer is preferably a non-nanostructured aluminum oxide layer, which is believed to act as a thermal barrier to the substrate and lower coating layers. Additional steps of depositing additional optional layers, including other non-nanostructured layers and a capping layer, may also be included. Furthermore, the method may also comprise the additional steps of pre-treating the substrate using a rotational stage and a mixture of compressed dry air and a pre-treatment abrasive medium prior to deposition of the coating onto the substrate and, after deposition of the coating layers onto the substrate, post-treating the coated with a mixture of water and post-treatment abrasive medium and a rotational stage driver to enhance the wear resistant and other properties of the coated substrate.

These and other features, objects and advantages of the present invention will become better understood from a consideration of the following detailed description of the preferred embodiments and appended claims in conjunction with the drawings as described following:

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIG. 1 is an illustration of one embodiment of the present invention, showing a coated substrate having a nanostructured coating comprising a single nanostructured layer deposited over the substrate.

FIG. 2 is an illustration of one embodiment of the present invention, showing a coated substrate having a nanostructured coating comprising a number of nanostructured layers deposited over the substrate and having an optional non-nanostructured layer deposited over the nanostructured layer.

FIG. 3 is an illustration of one embodiment of the present invention, showing a coated substrate having a nanostructured coating comprising a number of nano-structured layers and having a number of additional optional layers deposited on the substrate.

FIG. 4 is a photograph showing one embodiment of the present invention having a carbide insert with edge honing of 23 μm .

FIG. 5 is a photograph showing one embodiment of the present invention having a carbide insert with edge honing of about 12 μm .

FIG. 6 is an SEM photograph at a side elevational view of a cross-section of multiple coatings according to one embodiment of the present invention.

FIG. 7A is an SEM photograph top planar view of a cross-section of a nanostructured TiN layer according to one embodiment of the present invention.

FIG. 7B is an SEM photograph top planar view of a cross-section of a nanostructured TiCN layer according to one embodiment of the present invention.

FIG. 8 is an SEM photograph side elevational view of a cross-section of a nanostructured layer according to one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

With reference to FIG. 1, one embodiment of the present invention for use in connection with a cutting tool insert may be described. A substrate **10** forms a base for the tool insert. The substrate **10** is preferably selected from carbide or ceramic based substrates, and may be, for example, formed of cemented carbide or hard metals. Substrate **10** preferably comprises a grain size in the sub-micron and micron range of 0.1 to 1.5 microns and more preferably comprises an average grain size in the range of 0.4 to 0.8 microns. For example, substrate **10** may be a carbide substrate with tungsten carbide (TC) grain size in the range of sub-microns to microns range. For purposes herein, a sub-micron grain size means that the average size of grains is less than 1 μm in diameter in any direction but greater than nano-sized (i.e., greater than 100 nm in diameter in any direction), while a micron grain size means that the average size of grains is equal to or greater than 1 μm in any direction.

In one embodiment, substrate **10** may be a modified alumina substrate, which is tougher than alumina of either the alpha phase or kappa phase. It is preferred that substrate **10** comprises about 5.0 to 15.0 weight percent of cobalt or nickel as a binder. For example, the substrate may be a carbide substrate having a carbide matrix with submicron and micron sized tungsten carbide grains and a metallic binder phase comprising cobalt in the range of 5 to 12 percent. The substrate of the preferred embodiment has a radius hone in the range of about 0.0005" to 0.002", the radius hone preferably being matched to the overall coating thickness. The substrate also preferably has an edge honing of less than 30 microns, and more preferably between 8 and 20 microns. Finally, the substrate preferably has a hardness in the range of about 90 to about 93 HRA.

In on embodiment, substrate **10** may be pre-treated according to the method described below with a mixture of

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compressed dry air and a pre-treatment abrasive medium with particle size ranging from 10 to 150 microns, and more preferably from 30-80 microns. A suitable pre-treatment abrasive medium may include oxides and carbides, with the preferred abrasive medium being aluminum oxide. The pressure of the mixture may be in the range of 0.5 bar to 7.0 bar and is preferably from 1.0 bar to 3.5 bars. The following are non-limiting examples of substrates that may be used according to the present invention:

Substrate Example 1

A hard metal substrate having grain size between 0.1 to 1.5 micron and more preferably 0.4 to 0.8 micron average grain size. The substrate comprises a cobalt content (weight percentage) of 5 to 8 percent. The substrate also comprises a hardness of 91.8-93.3 HRA, a minimum transverse rupture strength of 275 ksi, a magnetic saturation of 110-150 emu/gram with grain growth inhibitors no more than 0.65%.

Substrate Example 2

A hard metal substrate having grain size between 0.1 to 1.5 micron and more preferably 0.4 to 0.8 micron average grain size. The substrate comprises a cobalt content (weight percentage) of 9 to 12 percent. The substrate also comprises a hardness of 91.0-92.8 HRA, a minimum transverse rupture strength of 350 ksi, a magnetic saturation of 110-150 emu/gram with grain growth inhibitors no more than 0.75%.

As indicated above, in one embodiment, a pre-treatment is applied to substrate **10** prior to depositing the coating layers onto substrate **10**. The pre-treatment may, for example, comprise a mixture of compressed air and pre-treatment abrasive medium having particle size in the range of 10 to 150 micron and more preferably in the range of 30 to 80 micron. The pre-treatment abrasive medium may include oxides and carbides and is preferably aluminum oxide. The pre-treated substrate may then be coated with the layers as described herein.

The substrate **10** of the cutting tool insert of the present invention is coated with a nanostructured coating **30** deposited over substrate **10** preferably by a chemical vapor deposition (CVD) process according to the method described herein. Nanostructured coating **30** may be a single coating layer (as shown in FIG. **1**) comprising a number of different functional particles or may be a series of sub-layers (as shown in FIGS. **2** and **3**) with each layer comprising one or more functional materials. For example, in one embodiment, coating **30** is a single nanostructured coating layer comprising titanium nitride (TiN), titanium carbo-nitride (TiCN), aluminum oxide (α -Al₂O₃), titanium carbide (TiC), and titanium nitride (TiN) (FIG. **1**), while in another embodiment, the nanostructured coating **30** may comprise multiple nanostructured layers: a first nanostructured layer **12** having TiN, a second nanostructured layer **14** having TiCN, and a third nanostructured layer **16** having TiCN (as shown in FIG. **2**).

For purposes herein, "nanostructured" may be defined as a coating layer that meets at least one of three different tests: a coating layer having a thickness of no greater than 100 nm; a coating layer containing particles of an average size no greater than 100 nm (as used herein, "nano-sized" particles); or a coating layer with grains that are nano-sized in the X-Y plane (that is, parallel to the plane in which coatings are applied), but not necessarily nano-sized in the direction perpendicular to the plane in which the coatings are applied. In this third case of nanostructured, it may be understood

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then that nano-sized may encompass particles that are "grown" on a surface with a vertical dimension that is greater than 100 nm yet still be within the scope of the meaning of nanostructured. Non-nanostructured, as used herein, means not meeting any of the three different tests for nanostructured; in other words, non-nanostructured refers to a coating layer having a thickness greater than 100 nm; particles of average size greater than 100 nm; and with grains measured in the X-Y plane having a size greater than 100 nm. FIG. **8** is an SEM photograph, taken in a direction parallel to the coating thickness, providing an example of this type of structure. FIG. **7A** is a TEM image, taken in a direction perpendicular to the coating thickness, showing a TiN where the individual nano-sized grains are visible in the nanostructure.

In the preferred embodiment, as shown in FIGS. **2** and **3**, a non-nanostructured layer is deposited over the nanostructured layer to create a nanostructured-to-non-nanostructured interface. may also be deposited onto substrate **10** to provide various functional enhancements. For example, a non-nanostructured aluminum oxide (α -Al₂O₃) layer **20** may be deposited over the nanostructured coating **30**, as shown in FIG. **2**. Other additional layers may be optionally deposited over the substrate (as shown in FIG. **3**), the functional aspects of each of the optional additional layers described more fully below.

As noted above, nanostructured coating **30** may be a single layer or a series of individual layers. The following description of individual layers **12**, **14**, and **16** describe the preferred embodiment of those layers where the nanostructured coating **30** comprises a series of individual layers.

Layer **12** is preferably a nanostructured layer of titanium nitride (TiN) with a thickness in the range of about 0.5 to 1.0 microns, with average grain size (measured on a plane perpendicular to the coating thickness) that is less than about 100 nm. It is believed that TiN layer **12** at this thickness provides a good interfacial layer because of its affinity for the material of substrate **10**. While the preferred embodiment involves a non-composite layer **12** composed of only TiN, alternative embodiments may include a composite of different materials, in some cases including TiN in the composite, in layer **12**.

Layer **14** is preferably a nanostructured layer of titanium carbonitride (TiCN) with a thickness in the range of about 0.5 to 1.0 microns. This layer **14** has a grain size (measured on a plane perpendicular to the coating thickness) of less than about 100 nm. As with layer **12**, it may be noted that the layer's grain size is not limited to nanoscale size when measured on a plane parallel to the coating thickness, and the result may thus be "long" grains that extend vertically in the direction of the coating thickness. FIG. **7B** is a TEM image, taken in a direction perpendicular to the coating thickness, showing a TiCN layer according to one embodiment, where the individual nano-sized grains are visible in the nanostructure. It is believed that thin TiCN layer **14** provides desirable properties because it provides a grain-size match to the material of layer **12**, thereby providing a minimum of stress at the point of the connection between these two layers, and providing a good transition to the next outer layer.

Layer **16** is preferably a second nanostructured layer of TiCN, with a thickness of about 2.0 to 3.0 microns. Again, it may be noted that the layer's grain size is not limited to nanoscale size when measured on a plane parallel to the coating thickness, and the result may thus be "long" grains that extend vertically in the direction of the coating thickness.

As noted above, in one embodiment one or more additional optional layers may be further deposited over the substrate for various functional requirements, as needed. The following descriptions of layers **18** and **22** provide examples of the preferred embodiments of various optional additional layers. It is understood that these optional additional layers may be implemented whether the nanostructured coating **30** is a single nanostructured layer or a series of individual nanostructured layers. Furthermore, it is understood that one additional optional layer may be utilized, multiple optional layers may be utilized in combination (as shown in FIG. **3** for example), or no optional layers may be utilized. Layer **18** is preferably a layer of carbon-enriched TiCN with a thickness of about 0.1 to 0.6 microns, and layer **22** is an optional capping layer, preferably comprising TiN, with a thickness of less than about 2.0 microns.

Finally, as noted above, a non-nanostructured layer **20** is preferably deposited over the nanostructured coating **30** to create a nanostructured-to-non-nanostructured interface. Layer **20** is preferably a layer of aluminum oxide (Al_2O_3), with a thickness of about 3.0 to 4.0 microns. This material is desirable as a thermal barrier to the substrate and lower coating layers on the insert.

In the preferred embodiment, the substrate coating (the nanostructured coating and non-nanostructured coating, including any sub-layers of those coatings, in combination) has a total thickness in the range of about 5 to 15 microns, but preferably is between 5 to 13 microns thick. For example, in one embodiment implementing a nanostructured coating of individual nanostructured layers **12**, **14**, and **16** in addition to non-nanostructured layer **20**, and additional optional additional layers **18** and **22**, the overall thickness of these six coatings, taken together, is preferably about 8 to 10 microns. FIG. **6** is an SEM photograph in cross-section showing an example of these layers, with the breaks between material layers clearly visible. The ordering of layers is reversed from FIG. **3**. It should be noted that although FIGS. **1-3** do not depict this aspect of the preferred embodiment, for the sake of clarity the coating layers in commercial embodiments should preferably extend over the edges of substrate **10**.

With respect to the preferred embodiment, grain size for the nanostructured layers as described above was performed using transmission electron microscopy (TEM) analysis, as is well understood in the art. Very thin samples (about 0.2 microns in thickness) were prepared with focused ion beam (FIB) methods. As may be seen in FIGS. **7A** and **7B**, average grain size is less than 100 nm for the nanostructured TiN and TiCN layers; the bar in the figures represents 50 nm. Again, the grain size was measured in the plane perpendicular to coating thickness, and thus the grain size in the plane parallel to coating thickness may be longer, as illustrated, for example, in FIG. **8**, where the bar at the right of the figure represents 3 microns.

As indicated above, in one embodiment a post-treatment is applied to the nanostructured coated substrate described above. The method of application of the post-treatment is described in detail below. The post-treatment comprises a mixture of water and post-treatment abrasive medium with particle size ranging from 0.2 micron to 50 microns and preferably from 5 microns to 20 microns. Suitable abrasive mediums include oxides and carbides with the preferred abrasive medium being aluminum oxides. The post-treatment mixture contains 5 to 50 percent (weight percent) of abrasive medium, and more preferably 20 to 40 weight

percent abrasive medium. The pressure of the post-treatment mixture ranges from 20 to 120 psi and more preferably from 40 to 80 psi.

The structure of a preferred embodiment of the present invention having now been presented, the preferred method for producing this structure may now be described. As noted above, the substrate **10** may be pre-treated with a mixture of compressed dry air and abrasive medium with particle size ranging from 10 to 150 micron, and more preferably from 30 to 80 micron. For this pre-treatment process, the substrates are loaded onto a planetary rotational stage with ten self-rotational poles. The rotational speed preferably ranges from 0.5 to 60 rpm. This pre-treatment process serves as an edge honing process for the substrate. The pre-treated substrate surface has a surface roughness (RMS) ranging from 0.05 to 1.5 micron and the honed edge has a radius ranging from 1.0 to 45 micron, and more preferably from 10 to 35 micron. Following this pre-treatment process, the multi-layer coating process occurs.

Nanostructured coating **30** is deposited using chemical vapor deposition techniques using a grain-refining agent. In the event multiple nanostructured layers are implemented in nanostructured coating **30**, TiN layer **12** is deposited using chemical vapor deposition (CVD) techniques using a grain-refining agent. In particular, the refining agent in the preferred embodiment is hydrogen chloride gas (HCl). The process is performed at a medium reactor temperature, specifically about 850° C. to about 920° C. in the preferred embodiment. It should be noted that HCl is generally seen as undesirable in CVD processes, since it tends to etch away or pit material that is being deposited, and thus slows the process of deposition. By slowing the process, it increases the cost of producing coated tool inserts. It has been found by the inventors, however, that HCl may be used to selectively etch or pit the layer as the deposition process moves forward in order to create nanostructured material. It is believed that the etching or pitting results in nucleation sites, that function to build nanostructure as the layer is deposited. The result, therefore, is a nanostructured layer of material that is produced at a relatively high rate of speed compared to what would be required to produce a similar layer without the refining agent. At this medium-temperature level, the grains produced are columnar, and thus within the definition of nanostructured as presented above.

Nanostructured TiCN layer **14** is also deposited using CVD techniques using the addition of HCl to produce a nanostructured layer. A medium-temperature process is employed, with a reactor temperature in this case of about 885° C. and reactor pressure of about 60 mbar. The second nanostructured TiCN layer **16** is applied at the same temperature, and again with added HCl, at a pressure of about 90 mbar. The TiCN with carbon enrichment layer **18** is deposited using a regular CVD process (no HCl added), at a higher temperature of about 1010° C. and reactor pressure of about 100 mbar.

Al_2O_3 layer **20** is deposited at a temperature of about 1005° to 1015° C. It may be noted that while certain references, such as U.S. Patent Publication No. 2006/0204757 to Ljungberg, teach that the Al_2O_3 layer desirably may be smoothed or fine-grained, it has been found by the inventors hereof that contrary to this teaching, roughness on this layer is not a detriment to the performance of the insert. For this reason, the inventors have been able to dramatically speed up the deposition process for this material as compared to prior art techniques, since slower deposition is required if a smooth finish is desired. In particular, the method of the preferred embodiment involves a deposition

time for this Al₂O₃ layer of about 210 minutes, compared to a typical time of deposition of a comparably sized Al₂O₃ layer in prior art techniques (where a smooth surface is achieved) of about 4 hours. The TiN capping layer **22** is then deposited on top in a conventional CVD process.

The table below provides a summary of process parameters and precursors for each of the layers deposited on substrate **10**.

Coating	H ₂	N ₂	HCl	TiCl ₄	CH ₃ CN	CH ₄	CO ₂	H ₂ S	Temp (° C.)	Pressure (mbar)	Duration (min)
n-TiN	53.4%	34.3%	4.67%	7.63%					930	160	60
n-TiCN	54.5%	31.1%	4.67%	9.34%	balanced				885	60	60
n-TiCN	54.5%	31.1%	4.67%	9.34%	balanced				885	90	180
TiCN	82.87%	5.53%		balanced		3.31%			1010	100	30
with carbon enriched layer											
Al ₂ O ₃	87.46%		8.81%				3.4%	balanced	1015	60	210
TiN	63.16%	26.31%		balanced					1015	100	30

The insert may be finished for cutting by the use of edge preparation techniques as known in the art, including grinding, wire brushing, or similar processes. Alternatively, the coated substrate may be post-treated following the coating process prior to being finished for cutting. As noted above, the insert surfaces may be post-treated with a mixture of water and abrasive medium having particle size ranging from 0.2 to 50 microns, and more preferably from 5 to 20 microns. The abrasive medium may include oxides and carbides and preferably consists of aluminum oxides. During the post-treatment process, the inserts are loaded onto rotational stages driven by a chain and motor such that the rotational speed is between 1 and 50 rpm. The resulting post-treated surface preferably has a surface roughness (RMS) ranging from 0.05 to 0.5 microns. Substrates that have been pre-treated, coated, and post-treated according to the method described herein are suitable for machining and may include nickel-cobalt alloys, titanium alloys, stainless steels, and steels. These inserts are also suitable for cutting operations including turning, grooving, threading, and index milling. While the multi-layer coating process as described herein results in cutting tool inserts with enhanced wear resistance and usage life, the addition of the pre-treatment and post-treatment is believed to increase the wear resistant and usage capabilities of the cutting tools even further. Examples of these results may be found with regard to the non-limiting examples provided below.

Example 1

In this case study, two cutting tool inserts were compared using semi-finish OD turning of rings of Inconel 718 alloys. The first insert was an RPGN-3V carbide grade (C2) substrate with up sharp edge in uncoated form. The second insert was a RPGN-3V carbide insert with a multiple-layer nanostructured coating according to the present invention. The nanostructured coating (TM20) comprised the following layered coating: TiN—TiCN(1)-TiCN(2)-α-Al₂O₃ with the first three layers in nanostructured form and the additional alumina layer in non-nanostructured form. The total thickness of the coating layer was 5-9 μm. The second insert comprised an edge of 10-20 μm. The tools were used at a surface speed of 200-225 SFM, a feed rate of 0.012 IPR, and

a depth cut of 0.01". The failure criteria selected were 0.025 mm flank wear and surface quality (surface finish and waviness) of workpiece quantified using surface profilometer and acoustic method. The results show a drastic increase in tool life for the cutting tool coated according to the present invention: 7-8 minutes of tool life for the non-coated substrate and a 30 minute tool life for the coated carbide substrate according to the present invention.

Example 2

In this case study, two cutting tool inserts were compared using OD turning of a low pressure turbine case made of aged 718 alloys. The first insert was a CVD coated RCMT43 S05F carbide grade (C2) substrate with an edge hone of 25-35 μm. The second insert was an RCMT43 TS2020 carbide insert with a multiple-layer nanostructured coating according to the present invention, where the substrate comprised a micron-grain carbide substrate with hardness of 92.4 and cobalt binder percentage of 6.1%. The nanostructured coating (applied by CVD) comprised the following layered coating in sequence: TiN—TiCN(1)-TiCN(2)-α-Al₂O₃ with the first three layers in nanostructured form and the alumina layer in non-nanostructured form. The total thickness of the coating layer was 9-13 μm. The second insert comprised an edge hone of 12-25 μm. The tools were used at a surface speed of 180 SFM, a feed rate of 0.012 IPR, and a depth cut of 0.04". The failure criteria selected were 0.025 mm flank wear and surface finish. The results show an increase in tool life for the cutting tool coated according to the present invention: 100 min tool life for the regular CVD coated substrate and 144 min tool life for the

Example 3

Cutting tests were performed in connection with a target material of American Iron and Steel Institute (AISI) 4340 hardened steel with severe interruptions. The inserts used for testing were CNMA432 carbide turning inserts, coated with nanostructured coatings in multi-layered form (individual nanostructured layers **12**, **14**, and **16**) and with additional layers **18**, **20**, and **22** as described above. A benchmark test was performed using the same type of insert (same style and grade) coated with conventional coating techniques with similar chemistry but micron-sized grains in each of the coating layers. The workpiece used was a material with a diameter of 6.0", with four deep, V-shaped slots in the peripherals to provide interruptions for testing, along with four 3/8" diameter through-holes evenly distributed on the end surface. Machining conditions were as follows:

Surface speed: 400 SFM
Feed rate: 0.0004 IPR

Depth of cut: 0.01"

Dry/wet: with cutting fluid

Failure criteria: 0.008" flank wear or 0.004" crater wear

With these test parameters and workpiece specifications as set out above, the benchmark insert demonstrated a tool life before failure, on average, of about 7 minutes. The insert prepared according to the preferred embodiment of the present invention, as previously described, produced an average tool life before failure of about 20 minutes. It may be seen therefore that the invention produced markedly improved performance over prior art coating techniques for cutting tool inserts, particularly when used in connection with the cutting of hardened steel with severe interruptions, which is known in the art as a particularly difficult material with respect to cutting tool insert life. The preferred embodiment may also find particular application where impact resistance is desired in a cutting tool insert.

The inventors believe that the combination of nanostructured layers with other layers that are not nanostructured may be responsible for the dramatically improved performance of the preferred embodiment. The matching of nanostructured and non-nanostructured materials may produce a unique combinatorial architecture delivering dramatically improved results, achieving a cutting tool insert that is less prone to chip-off failure and flank wear problems. The transition from inner layers to outer layers of smaller-scaled to larger-scaled particles may create a better bond between the layers of the coating and between the coating and the substrate. This structure may also result in fewer stress points—or may compensate for stress points that result from material discontinuities/defects—within the structure of the substrate/coating matrix. The presence of stress points within the coating structure are believed by the inventors hereof to correlate with premature wear or failure.

Example 4

This example shows the performance enhancements obtained by pre- and post-treatment of the coated substrates. RPGN-3V inserts were used at the following conditions for semi-finishing and finishing Ti-17 alloys.

Surface speed: 200 to 225 SFM

Feed rate: 0.012 IPR

Depth of cut: 0.01" (per side)

At identical tool failure criteria of 0.012" flank wear and workpiece surface finish of 12 FMS, multi-layer coated RPGN-3V TM2005 substrates with submicron grain size, 6.0% cobalt, hardness of 92.8 HRA and total thickness of 7.0 to 9.0 microns, which were pre-treated and post-treated to obtain a surface roughness of 0.5 micron, produced tool life of about 20 minutes, whereas other products of identical geometry, RPGN-3V, from top OEMs produced only 7 to 8 minutes of tool life.

Example 5

Again, this example shows the performance enhancements obtained by pre and post treatment of substrates. RPGN-3V inserts were used at the following conditions for semi-finishing and finishing 718 inconel alloys (with hardness of more than 40 HRC):

Surface speed: 200 to 225 SFM

Feed rate: 0.012 IPR

Depth of cut: 0.01" (per side)

At identical tool failure criteria of 0.012" flank wear and workpiece surface finish of 12 FMS, multi-layer coated RPGN-3V TM2005 substrates with submicron grain size,

6.0% cobalt, hardness of 92.8 HRA and total thickness of 7.0 to 9.0 microns, which were pre-treated and post-treated to obtain a surface roughness of 0.5 micron, produced tool life of about 30 minutes, whereas other products of identical geometry, RPGN-3V, from top OEMs produced only 7 to 8 minutes of tool life.

These examples show that a substrate coated with nanostructured coating and optional additional coating layers not only improves tool performance, but that pre-treatment and post-treatment of these substrates delivers performance enhancement for inserts used in turning titanium alloys and nickel-cobalt alloys. This same performance enhancement may be recognized in machining using stainless steels and steels among others.

As used herein, "comprising" is synonymous with "including," "containing," or "characterized by," and is inclusive or open-ended and does not exclude additional, unrecited elements or method steps. As used herein, "consisting of" excludes any element, step, or ingredients not specified in the claim element. As used herein, "consisting essentially of" does not exclude materials or steps that do not materially affect the basic and novel characteristics of the claim. Any recitation herein of the term "comprising", particularly in a description of components of a composition or in a description of elements of a device, is understood to encompass those compositions and methods consisting essentially of and consisting of the recited components or elements. The invention illustratively described herein suitably may be practiced in the absence of any element or elements, limitation or limitations which is not specifically disclosed herein.

When a Markush group or other grouping is used herein, all individual members of the group and all combinations and subcombinations possible of the group are intended to be individually included in the disclosure.

The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the appended claims. Thus, additional embodiments are within the scope of the invention and within the following claims.

In general the terms and phrases used herein have their art-recognized meaning, which can be found by reference to standard texts, journal references and contexts known to those skilled in the art. The preceding definitions are provided to clarify their specific use in the context of the invention.

All patents and publications mentioned in the specification are indicative of the levels of skill of those skilled in the art to which the invention pertains. All references cited herein are hereby incorporated by reference to the extent that there is no inconsistency with the disclosure of this specification.

The present invention has been described with reference to certain preferred and alternative embodiments that are intended to be exemplary only and not limiting to the full scope of the present invention as set forth in the appended claims.

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The invention claimed is:

1. A cutting tool insert, comprising:
 - a. a pre-treated carbide substrate with a hardness range of 90 to 93 HRA that has been treated with a first abrasive material having a particle size ranging from 30 to 80 microns resulting in said pre-treated carbide substrate comprising an average tungsten carbide grain size of 0.4 to 0.8 microns, a honing edge in the range of 10 and 35 microns, and a surface roughness of 0.05 to 1.5 micron, further wherein the pre-treated carbide substrate comprises a metallic binder phase comprising cobalt in the range of 5 to 14 percent;
 - b. at least one nanostructured layer, wherein a first at least one nanostructured layer is deposited over the pre-treated carbide substrate, and if applicable, followed by depositing a series of additional at least one nanostructured layers, one at a time, over a prior at least one nanostructured layer until application of a final at least one nanostructured layer resulting in a nanostructured coating, wherein each at least one nanostructured layer is selected from a group consisting of titanium carbonitride, titanium carbide, and titanium nitride;
 - c. a carbon enriched layer deposited over the nanostructured coating wherein the carbon enriched layer comprises carbon enriched titanium carbonitride; and
 - d. a non-nanostructured layer deposited over the carbon enriched layer wherein the non-nanostructured layer comprises an aluminum oxide layer that has been post-treated with a second abrasive material having a particle size ranging from 5 to 20 microns resulting in a post-treated aluminum oxide layer with a surface roughness ranging from 0.05 to 0.5 microns;
 wherein the first and second abrasive materials are a carbide or aluminum oxide.
2. The cutting tool insert of claim 1, wherein the first at least one nanostructured layer comprises a thickness in the range of about 0.5 to about 1.0 microns, further wherein the first at least one nanostructured layer consists essentially of titanium nitride.
3. The cutting tool insert of claim 2, wherein the nanostructured coating further comprises a second nanostructured layer deposited over the first at least one nanostructured layer, wherein the second at least one nanostructured layer comprises a thickness in the range of about 0.5 to about 1.0 microns, further wherein the second at least one nanostructured layer consists essentially of titanium carbonitride.
4. The cutting tool insert of claim 3, wherein the nanostructured coating further comprises a third at least one

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nanostructured layer deposited over the second at least one nanostructured layer, wherein the third at least one nanostructured layer comprises a thickness in the range of about 2.0 to about 3.0 microns, further wherein the third nanostructured layer consists essentially of titanium carbonitride.

5. A cutting tool insert, comprising:
 - a. a pre-treated substrate with an average tungsten carbide grain size of 0.4 to 0.8 microns, a honing edge in the range of 10 and 35 microns, and a surface roughness of 0.5 to 1.5 micron;
 - b. a nanostructured coating deposited over the substrate, the nanostructured coating comprising
 - i. a first nanostructured layer deposited over the pre-treated substrate;
 - ii. a second nanostructured layer deposited over the first nanostructured layer; and
 - iii. a third nanostructured layer deposited over the second nanostructured layer;
 - c. a non-nanostructured layer deposited over the nanostructured coating wherein the non-nanostructured layer comprises an aluminum oxide layer that has been treated with an abrasive material having a particle size ranging from 5 to 20 microns resulting in a post-treated aluminum oxide layer with a surface roughness ranging from 0.05 to 0.5 microns; and
 - d. a nanostructured-to-non-nanostructured interface at a face of the non-nanostructured layer in contact with the nanostructured layer, thereby forming a coated substrate,
 wherein said pre-treated substrate consists of a carbide or a modified alumina substrate that further comprises a metallic binder phase comprising cobalt or nickel in the range of 5 to 14 percent with a hardness range of 90 to 93 HRA that has been treated with a carbide or aluminum oxide particle having a particle size ranging from 30 to 80 microns.
6. The cutting tool insert of claim 5, wherein the first nanostructured layer consists of titanium nitride.
7. The cutting tool insert of claim 6, wherein the second nanostructured layer consists of titanium carbonitride.
8. The cutting tool insert of claim 7, further wherein the third nanostructured layer consists of titanium carbonitride.
9. The cutting tool insert of claim 8, further comprising a capping layer.
10. The cutting tool insert of claim 9, wherein a total combined thickness of the first and second nanostructured layers on the substrate is 1.0 to 2.0 microns.

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